

A deep photometric survey of the η Chamaeleontis cluster down to the brown dwarf – planet boundary

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ABSTRACT

We report the outcome of the deep optical/infrared photometric survey of the central region (33×33 arcmin or 0.9 pc^2) of the η Chamaeleontis pre-main sequence star cluster. The completeness limits of the photometry are $I = 19.1$, $J = 18.2$ and $H = 17.6$; faint enough to reveal low mass members down to the brown dwarf and planet boundary of $\approx 13 M_{Jup}$. We found no such low mass members in this region. Our result combined with a previous shallower ($I = 17$) but larger area survey indicates that low mass objects ($0.013 < M/M_{\odot} < 0.075$) either were not created in the η Cha cluster or were lost due to the early dynamical history of the cluster and ejected to outside the surveyed areas.

Key words: stars: pre-main-sequence — stars: fundamental parameters — open clusters and associations: individual: η Chamaeleontis

1 INTRODUCTION

The nature of the initial mass function (IMF) for brown dwarfs and their spatial distribution hold important keys to the dominant brown dwarf formation mechanism in star clusters. This will provide a solution to the formation mechanism of brown dwarfs; whether brown dwarfs are stellar embryos, ejected from unstable newborn multiple systems before they can accrete sufficient mass for hydrogen fusion (Papaloizou & Terquem 2001; Reipurth & Clarke 2001; Bate et al. 2003; Delgado-Donate et al. 2003; Kroupa & Bouvier 2003; Sterzik & Durisen 2003); or hydrostatic cores that lose their accretion envelopes because of encounters with other protostars in rich clusters (Price & Podsiadlowski 1995); or by photo-evaporation of their accretion envelopes through nearby O stars (Kroupa et al. 1999; Matsuyama et al. 2003; Whitworth & Zinnecker 2004); or if they form in the same way as stars (Shu et al. 1987; Briceno et al. 2002; White & Basri 2003; Padoan & Nordlund 2004).

The recently discovered η Chamaeleontis cluster (η Cha hereafter; Mamajek et al. 1999) is an ideal target to study

the lowest mass objects due to its youth ($t \simeq 8$ Myr, Lawson & Feigelson 2001; Zuckerman & Song 2004), compact size (extent ~ 1 pc), and proximity to Earth ($d \sim 97$ pc). Negligible foreground reddening has been determined for η Cha [HD 75416, $E(b - y) = -0.004$; Westin 1985] simplifying photometric analysis. These characteristics of the η Cha cluster enable conventional photometric surveys with medium size telescopes (3 – 4 m aperture) to detect candidate members even in the planetary mass range. In addition, the compactness of the cluster compared to other nearby young stellar associations is an advantage for attempting to determine complete cluster membership down to very low masses. On the contrary, a deep photometric membership survey of the TW Hydrae association (TWA) (size $> 500\text{deg}^2$ in the sky plane), which like the η Cha cluster also appears to share a common kinematic link with the subgroups of the Ophiuchus-Scorpius-centaurus OB association (Mamajek et al. 2000), is not practical and likely contains too many field interlopers.

To date, 18 primaries have been discovered in the η Cha cluster with a mass range from $0.15 M_{\odot}$ to $3.4 M_{\odot}$ (Mamajek et al. 1999; Lawson et al. 2002; Lyo et al. 2004; Song et al. 2004; Luhman & Steeghs 2004). By extending the cluster IMF to lower masses, Lyo et al. (2004) predicted that 10 – 14 additional low mass stars with $M/M_{\odot} = 0.08 - 0.15$

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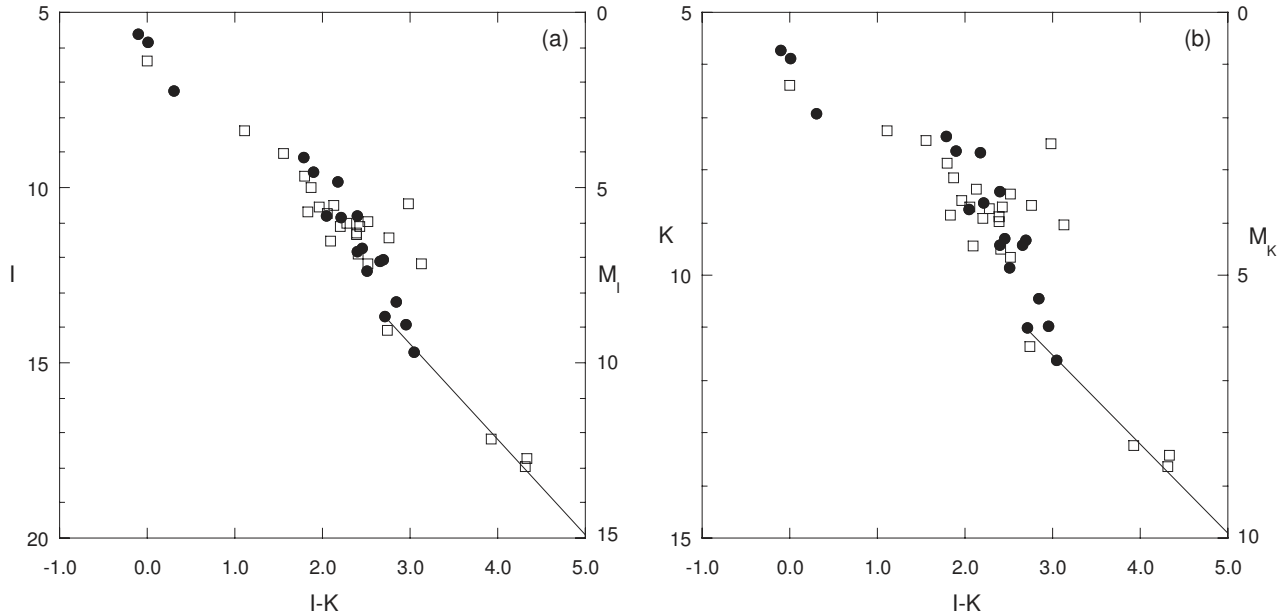


Figure 1. (a) I versus $(I - K)$ and (b) K versus $(I - K)$ colour-magnitude diagrams of the known members of the η Cha cluster and TW Hydrae association. The right-hand-side axes are marked in absolute magnitudes. The filled-circles are for the members of the η Cha cluster, while the open-squares are for members of the TWA if placed at the η Cha distance of $d = 97$ pc (see Mamajek 2005 for distances to the TWA members). The scatter in magnitude at any given colour is principally a function of unaccounted for multiplicity. The straight solid line in each graph represents a ~ 10 Myr (the approximate age of the η Cha and TWA groups) pseudo-isochrone for very low-mass stars and brown dwarfs to obtain the relationship between I - and K -band luminosity; see Section 1.

and 10–15 brown dwarfs with $M/M_{\odot} = 0.025 - 0.08$ remain to be discovered, a number of objects comparable to the already known stellar population. An alternative calculation is to use the IMF relationships for the mass of the stellar membership of a cluster put forward by Weidner & Kroupa (2006; see their figs 1 and 6). For the η Cha cluster, the Weidner & Kroupa relations also predict a total population greatly in excess of the known population, with ≈ 90 objects with $M > 0.01M_{\odot}$.

In a recent search for low mass members of the η Cha cluster, Luhman (2004) found no new members within a radius of 1.5° surrounding η Cha using DEep Near Infrared Survey (DENIS) and Two Micron All Sky Survey (2MASS) photometric data. Using Baraffe et al. (1998) and Chabrier et al. (2000) pre-main sequence tracks and a modified luminosity-colour-temperature sequence, Luhman claimed his survey was complete (at the $i = 17$ completeness limit of the DENIS survey) for low mass objects within a mass range of $M/M_{\odot} = 0.015 - 0.15$. However, the actual mass range is very sensitive to the adopted isochrone, which has been poorly defined by observations in the brown dwarf regime for ~ 10 Myr-old objects. Recently, Mamajek (2005) has calculated kinematic distances to members of the TWA which has a similar age (~ 10 Myr) to that of the η

Cha cluster. The TWA includes three brown dwarfs with masses of $20 - 25 M_{Jup}$ determined from the DUSTY tracks of Chabrier et al. (2000) and other lines of evidence. These three objects are the $\sim 25 M_{Jup}$ 2MASSW J1207334-393254 and 2MASSW J1139511-315921 (Gizis 2002) and the $\sim 20 M_{Jup}$ SSSPM J1102-3431 (Scholz et al. 2005). If these objects are placed at the distance of the η Cha cluster, they all fall below the $i = 17$ mag limit of the DENIS survey, suggesting that a DENIS-based survey of the η Cha cluster is limited to $M \gtrsim 25 M_{Jup}$ objects.

We also obtain this same mass limit directly from the mass-luminosity relation from the DUSTY models (Chabrier et al. 2000), making use of the absolute K -band magnitudes for the TWA brown dwarfs. Using the K -band luminosity to obtain the mass is acceptable as most of the flux in young very low-mass objects is released in the near-infrared (the peak flux of the lowest-mass objects arises at $\sim 1\mu\text{m}$). Recently, Close et al. (2005) reported that the predicted mass of AB Dor C from the K -band flux ($0.070 M_{\odot}$) compared reasonably well to their dynamical mass of $0.090 \pm 0.005 M_{\odot}$ obtained through direct imaging, even if it is still a significant (20 per cent) underestimate. (Close et al. also warn about the danger of using evolutionary tracks at ages that have not been sufficiently calibrated by observations). Fig.

1(a) shows the I versus $(I - K)$ colour-magnitude diagram for the known members of the η Cha cluster and the TWA. We plotted the members of the TWA as if they were located at the $d = 97$ pc distance to the η Cha cluster (see Mamajek 2005 for kinematic distances to the TWA members). Together these observations map the ~ 10 Myr isochrone across spectral types ranging from B8 (η Cha itself; $M = 3.4 M_{\odot}$) to the three M8 – M8.5 TWA brown dwarfs with masses of 20 – 25 M_{Jup} . The straight solid lines in Figs 1(a) and 1(b) approximately map the isochrone across the brown dwarf mass regime in these colour-magnitude diagrams. From this observational isochrone, we conclude the mass limit of the DENIS survey to be $\sim 25 M_{Jup}$ using the observed mass and K-band magnitude relation (Fig. 1b), in conjunction with the 5 Myr and 10 Myr DUSTY models (also see Section 2 for further discussion of this calibration).

In this paper, we report the result of the deepest optical/infrared photometric survey attempted on the η Cha cluster to date. The new observations that we report here extend the DENIS and 2MASS surveys by $\simeq 2$ magnitudes. We show that our survey is sensitive to low-mass objects near the brown dwarf – planet boundary with $M \approx 0.013 M_{\odot}$.

2 OBSERVATIONS AND DATA REDUCTION

An I -band image of the η Cha cluster was obtained in service mode using the 3.9-m Anglo-Australian Telescope (AAT) and Wide Field Imager (WFI) on 2004 January 20. WFI is an $8k \times 8k$ CCD mosaic (eight 2048×4096 $15\text{-}\mu\text{m}$ square pixel MIT/LL CCDs) for optical imaging at the prime focus. The image scale is 0.23 arcsec pixel $^{-1}$ at $f/3.3$, covering a 33×33 arcmin field (Fig. 2). The exposure time was 60 sec and the seeing was ~ 1.5 arcsec. The WFI I -band image was overscan corrected, bias and dark subtracted, linearized, and flat-fielded using the IRAF/MSCRED package. We then split this mosaic frame into eight individual CCD images using MSCRED/mscsplit for further photometric reduction.

JH -band images of almost the same field as the WFI I -band image were obtained on 2004 April 5 in service mode with the AAT using the $1.0 - 2.5\mu\text{m}$ infrared imager and longslit/multi-slit spectrograph (IRIS2). IRIS2 uses a 1024×1024 Rockwell HAWAII-1 HgCdTe infrared detector which has a plate scale of 1.45 arcsec pixel $^{-1}$, giving a field of 7.7×7.7 arcmin at the $f/8$ Cassegrain focus. We obtained 22 images with 3×9 -s exposure cycles (27-s total exposure time at each position) in each filter covering the central $\sim 30 \times 30$ arcmin region of the cluster. Unfortunately, the seeing was quite variable in each of the image fields, ranging between 1.5 and 3.0 arcsec. However, conditions remained photometric. The raw images were pre-processed using the ORAC-DR data reduction pipeline (Economou et al. 1998).

Instrumental magnitudes from the WFI I -band and IRIS2 JH -band data were obtained using the IRAF/DAOPHOT task via point-spread function fitting. For the calibration of the I -band photometry, we used photometry from the DENIS *Gunn-i* ($0.82 \mu\text{m}$) survey. For the JH -band data, we used 2MASS J ($1.25 \mu\text{m}$) and H ($1.65 \mu\text{m}$) photometry. We selected well-isolated objects with DENIS and 2MASS data to transform instrumental into real magnitudes using independent calibrations for each frame and filter. We did not

consider colour terms in these transformations because we have only one optical band and the JH -band data did not show any definite colour term. For the WFI I -band observations, the scatter in these magnitude transformations (to check the accuracy of the magnitudes) was 0.07 mag (0.16 mag) for stars brighter (fainter) than $I = 17$. For the IRIS2 J - and H -band observations, the scatter was typically 0.06 mag (0.08 mag) for stars brighter (fainter) than ~ 16 mag at J or H -band. Scatters are slightly larger for fields with the poorest seeing. However, such scatter has little influence on our results as we show in Fig. 3.

Fig. 3 shows the WFI/IRIS2 $(I - J)$ versus I colour-magnitude diagram, with our survey photometry shown as plus symbols. To show the diagram space occupied by cluster members and any candidate members, we overplot the known primaries. The filled-circles are photometry for the 18 known primaries of the η Cha cluster, while the open-squares are photometry for the members of the TWA after correcting their magnitudes to the η Cha distance (Mamajek 2005). Late-type stars and brown dwarfs associated with the η Cha cluster will be clearly elevated in magnitude above the vast majority of field stars. The typical uncertainties in our survey photometry can be neglected compared to the wide range in magnitude and colour plotted in Fig. 3.

The two long-dashed lines in Fig. 3 are the 5 Myr ($0.008 - 0.075 M_{\odot}$) and 10 Myr ($0.012 - 0.08 M_{\odot}$) isochrones from the DUSTY brown dwarf models of Chabrier et al. (2000). These model isochrones under-estimate the I -band magnitude by 1–2 mag (and also under-estimate the colour) of low-mass stellar members (M4-5 stars near $I = 14$) but approximately predict the properties of objects near the brown dwarf – planet boundary (near $I = 18$). The solid-line is our assumed locus of ~ 10 Myr-old objects to select low-mass star and brown dwarf candidates of the η Cha cluster. An apparent candidate at $I \approx 14$ and $(I - J) \approx 2.0$ is a known M4.7 member, ECHA J0841.5–7853, with WFI/IRIS2 photometry that differs only slightly from already-published values. There are no other obvious new candidate cluster members.

To see if we missed any other objects of interest, we checked all red ($J - H$) sources in the $(J - H)$ versus J colour-magnitude diagram (Fig. 4). Objects plotted as crosses are those that do not appear in the WFI I -band images, while those plotted as empty-plus signs are saturated in the J -band images (with $J \gtrsim 13$). As in Fig. 3, the solid line represents our criterion for cluster candidates in this colour-magnitude plane. Inspection of images of the three objects marked as crosses that reside close to the solid line with $J \approx 16$ reveals them to be galaxies.

The completeness limit of the photometry which is the peak magnitude of the luminosity function are $I = 19.1$, $J = 18.2$, and $H = 17.6$, respectively. These completeness limits are generally about 1 mag brighter than the magnitude of the faintest stars measured.

3 RESULTS

We report the outcome of a deep optical and infrared photometry survey of the central regions of the η Cha star cluster (33×33 arcmin), corresponding to an area of 0.9 pc^2 at the distance to the cluster of $d = 97$ pc. The complete-

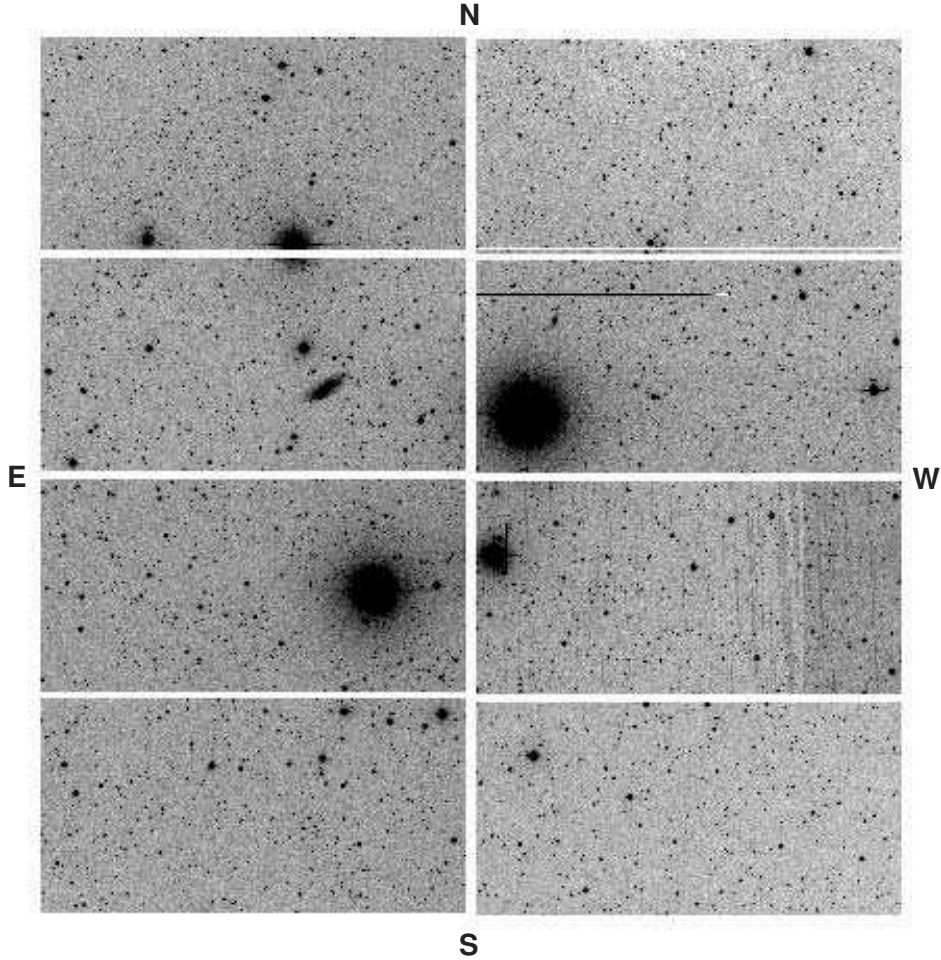


Figure 2. 33×33 arcmin WFI *I*-band image of the η Cha cluster core region centered at α, δ (2000) = $8^{\text{h}}41^{\text{m}}59.9^{\text{s}}, -79^{\circ}00'00''$; the spatial center of the three early-type systems in the cluster. The combined coverage of the IRIS2 *JH*-band images is almost the same as the *I*-band field; see Section 2 for details.

ness of the photometric data implies that our survey could reveal members down to the brown dwarf – planet boundary of $\sim 0.013 M_{\odot}$, but we found no such low mass cluster candidate members.

This null result indicates that either low mass objects were not created in the η Cha cluster or, if they were created, then they have been dynamically scattered outward after their birth. The former would suggest an unusual IMF for the cluster, highly deficient in both low-mass stars and brown dwarfs. This result would be surprising given the apparent near-universality of the IMF, unless sparse star clusters such as η Cha are unusual as our null result may suggest. Dynamical scattering of low mass stars may still be plausible despite the fact that Luhman (2004) did not find any low-mass candidate of the η Cha cluster within a distance of 1.5° from the cluster center. The present compact state of the cluster suggests that it is not dynamically relaxed, and hints at its early dynamical history. Adopting values from Lyo et al. (2004), the observed half-mass ($M \approx 10 M_{\odot}$) radius of $r \approx 5$ arcmin = 0.15 pc yields a *current* dynamical crossing time of $t_{ct} \approx 600,000$ yr; a timescale that may have been considerably shorter in the past if the cluster was more-massive (contained more members) and/or physically more-

compact. For an age of $t \sim 10$ Myr, this calculation suggests the η Cha cluster is dynamically moderately-evolved, with the core having persisted for a few tens of crossing times. Stars ejected from the cluster during the first few t_{ct} need only be imparted a velocity of $\gtrsim 0.3 \text{ km s}^{-1}$ to be removed $r > 1.5^{\circ} = 2.5$ pc from the core. The possibility remains that a halo population of low mass objects at radii of several degrees surrounds the observed remnant cluster core.

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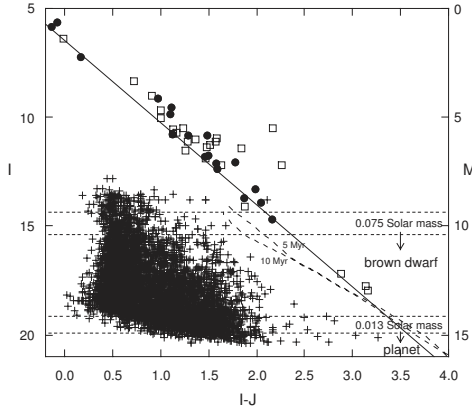


Figure 3. The I versus $(I - J)$ colour-magnitude diagram for stars in the $\approx 33 \times 33$ arcmin surveyed region of the η Cha cluster. The right-hand-side axis is marked in absolute magnitude. The filled-circles are for the known members of the η Cha cluster. Open-squares are for the members of the TWA if placed at the η Cha distance (see Mamajek 2005 for distances). The scatter in magnitude at any given colour is principally a function of unaccounted for multiplicity. The two long-dashed lines are the 5 Myr ($0.008 - 0.075 M_{\odot}$) and 10 Myr ($0.012 - 0.08 M_{\odot}$) DUSTY model isochrones of Chabrier et al. (2000). The solid-line is our criterion to choose low-mass star/brown dwarf candidates. The horizontal short-dashed lines are the $0.075 M_{\odot}$ and $0.013 M_{\odot}$ brown dwarf mass boundaries derived from the mass and K -band luminosity relations given within the 5 Myr and 10 Myr DUSTY models. We estimated the I -band magnitudes corresponding to this brown dwarf mass range using the observed IK colour-magnitude relations shown in Fig. 1. These relations show our survey is sensitive to brown dwarf masses down to the $\approx 0.013 M_{Jup}$ brown dwarf – planet boundary.

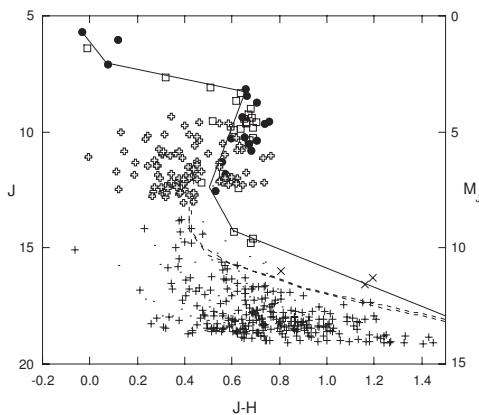


Figure 4. The J versus $(J - H)$ colour-magnitude diagram for the central regions of η Cha cluster from our IRIS2 JH data. The right-hand-side axis is marked in absolute magnitude. Symbols have the same meaning as in Fig. 3 except that crosses and empty-plus symbols denote undetected or saturated objects, respectively, in the WFI I -band images.

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